



Bio-Optimized Technologies to keep Thermoplastics
out of Landfills and the Environment

DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

BOTTLE 1 – Introduction & BOTTLE Overview

April 3, 2023

Technology Session Review Area: Plastics Deconstruction and Redesign

PI: Gregg T. Beckham, BOTTLE CEO, National Renewable Energy Laboratory

Presenters: Gregg Beckham, Meredith Doyle, BOTTLE COO, and Michelle Reed, BOTTLE Project Manager

Science Leadership Team:

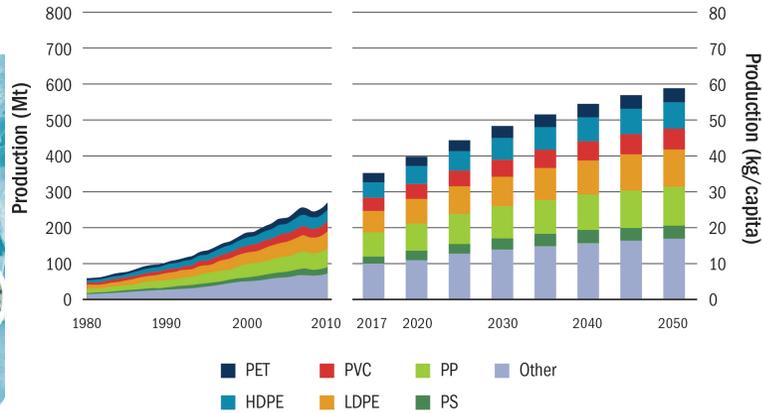
Bob Allen, National Renewable Energy Laboratory; Linda Broadbelt, Northwestern University; Alberta Carpenter, National Renewable Energy Laboratory; Eugene Chen, Colorado State University; Taraka Dale, Los Alamos National Laboratory; Jennifer DuBois, Montana State University; Adam Guss, Oak Ridge National Laboratory; Katrina Knauer, National Renewable Energy Laboratory; Andrew Pickford, University of Portsmouth; Yuriy Román-Leshkov, Massachusetts Institute of Technology; Christopher Tassone, SLAC National Accelerator Laboratory; Meltem Urgun-Demirtas, Argonne National Laboratory

Overview and history of the BOTTLE Consortium

Why should DOE work on plastics circularity?

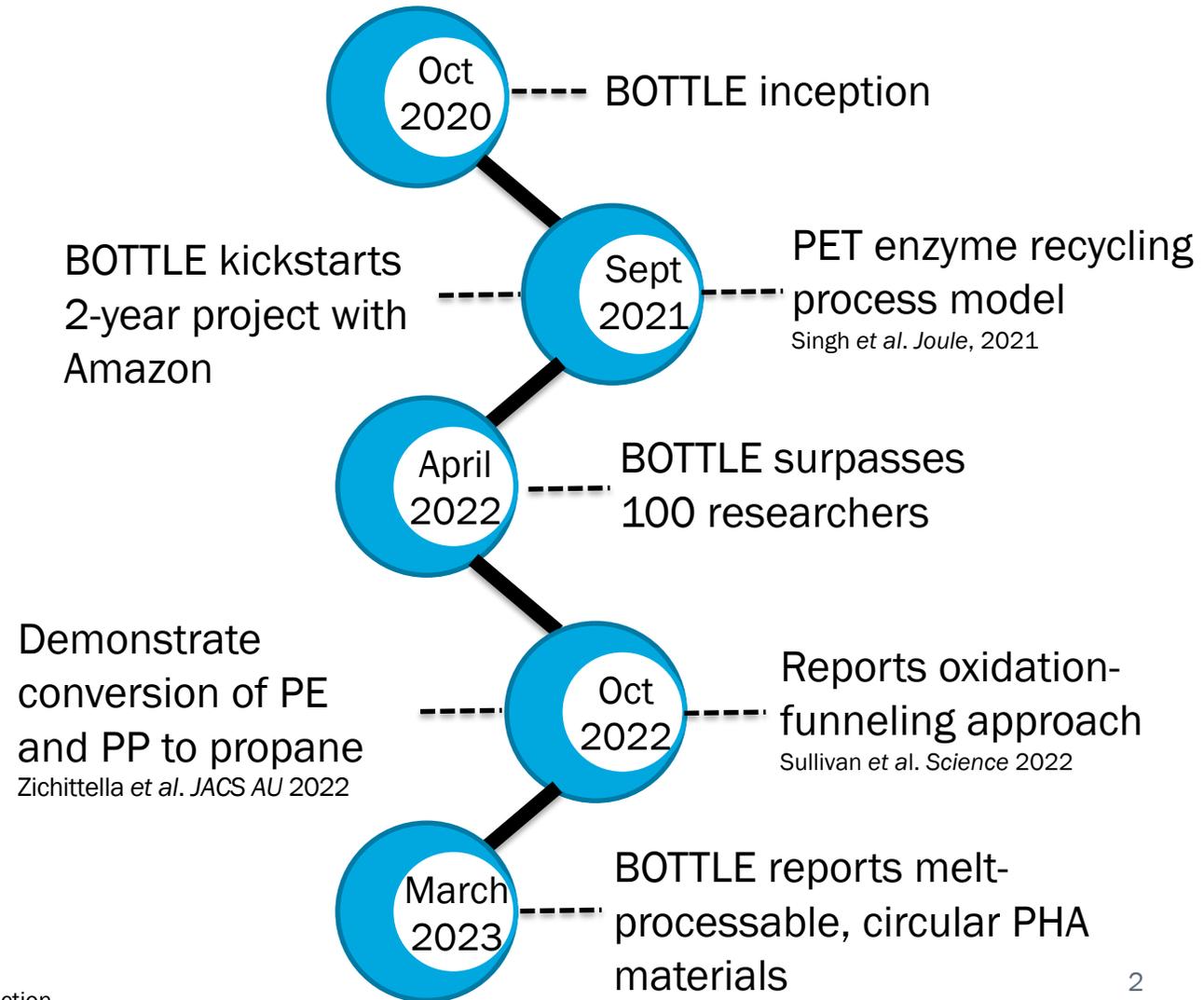
Strategy for Plastics Innovation

U.S. Department of Energy



- ~2-3% of total energy consumption in the US is used to manufacture plastics, resins, and synthetic rubber
- Plastic production generates ~3.8% of global GHGs
- Plastic production uses ~6% of global oil production, representing a large opportunity for further energy and process efficiency improvements

BOTTLE's history so far...



BOTTLE vision, mission, goals, and DEI

Vision

- Deliver scalable technologies that enable cost-effective recycling, upcycling, and energy efficiency for plastics

Mission

- Develop robust processes to upcycle existing waste plastics, and
- Develop new plastics and processes that are recyclable-by-design

Goals

- Work with industry to catalyze new recycling and redesign paradigms
- Leverage DOE investments in process development, catalysis, materials, and analysis-driven R&D

DEI

- A diverse and inclusive consortium that fosters the growth of researchers across their career, engages broadly to educate the public on our work, and ultimately contributes to the local community and the world broadly



Strategic Goals

1. **Deconstruction:** Create new chemical, thermal, and biological/hybrid pathways to deconstruct plastics efficiently into useful chemical intermediates.
2. **Upcycling:** Advance the scientific and technological foundations that will underpin new technologies for upcycling chemical intermediates from plastic waste into high-value products.
3. **Recyclable by Design:** Design new and renewable plastics and bioplastics that have the properties of today's plastics, are easily upcycled, and can be manufactured at scale domestically.
4. **Scale and Deploy:** Support an energy- and material-efficient domestic plastics supply chain by helping companies scale and deploy new technologies in domestic and global markets, while improving existing recycling technologies such as collection, sorting, and mechanical recycling.

Aligning
BOTTLE
tasks:



Deconstruction



Upcycling



Redesign



Industry
Engagement

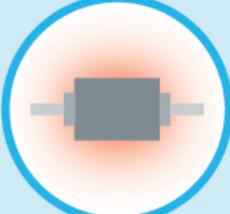
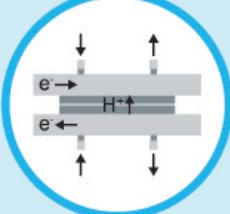
Plastic Waste

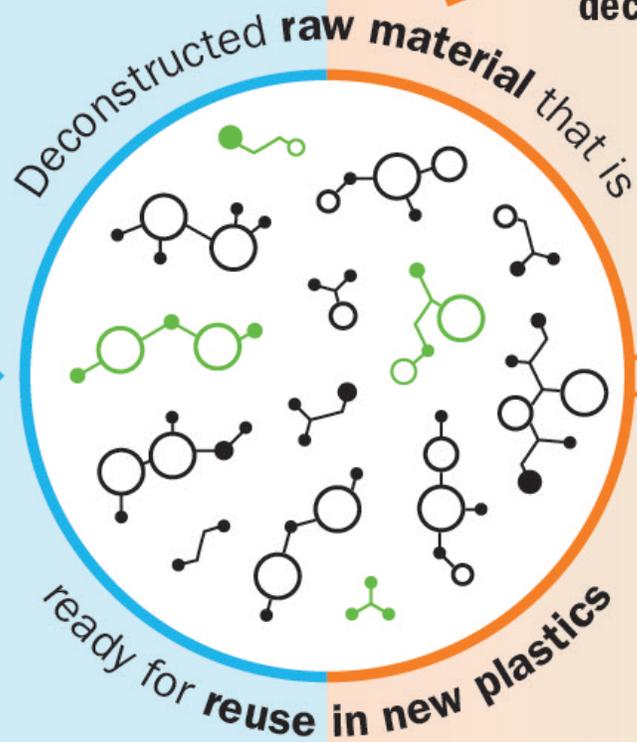
Deconstruction

Upcycling + Redesign



Plastic goods are broken down using various **biological** and **chemical** processes

-  Thermal Catalysis
-  Electrocatalysis
-  Biocatalysis
-  Photocatalysis

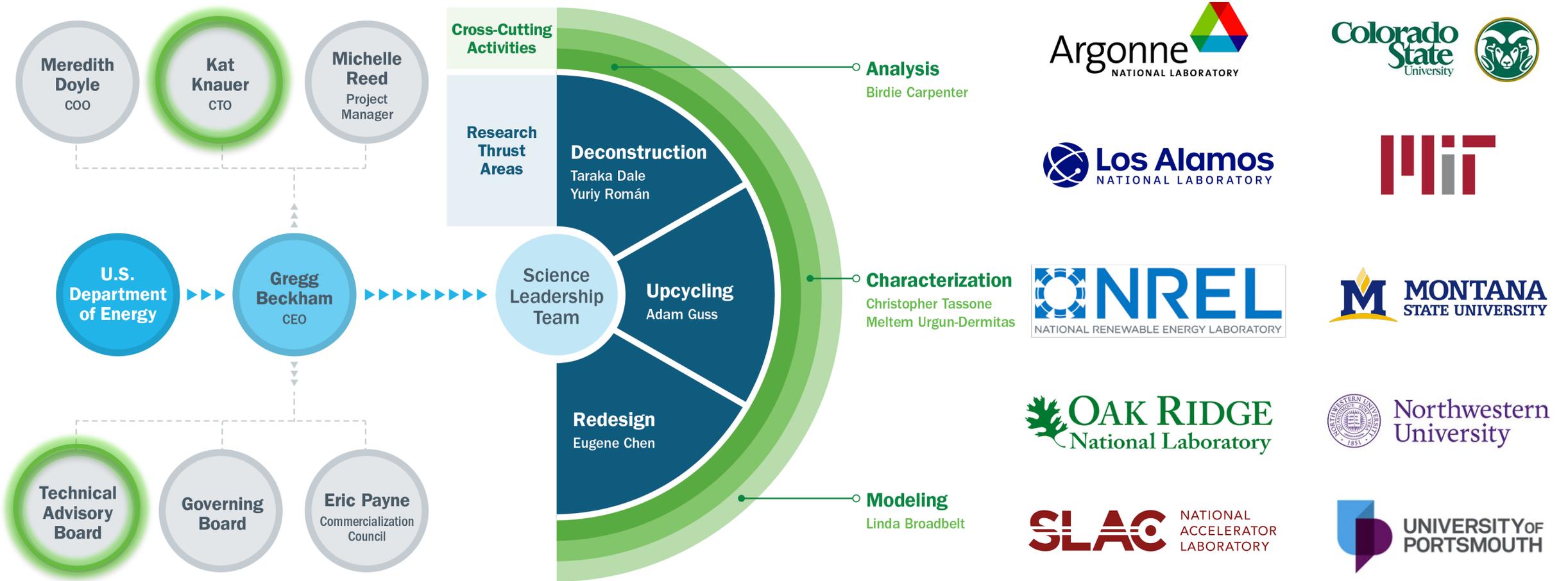


New plastic goods are created that are **recyclable by design**

These new plastic goods can be **deconstructed again**



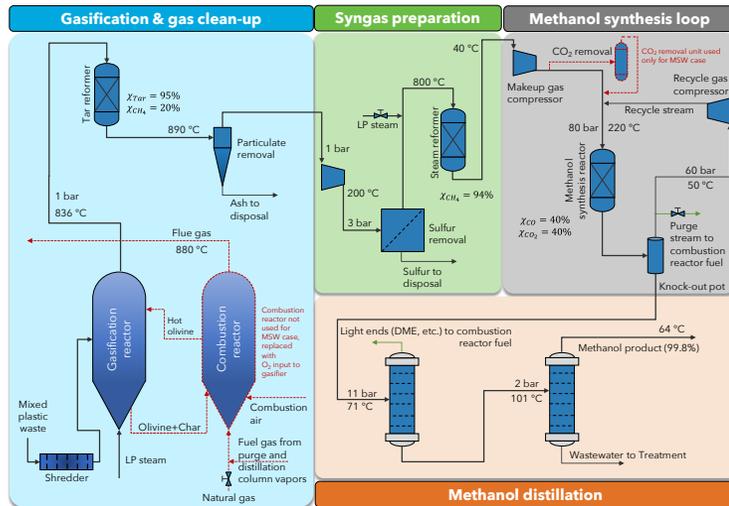
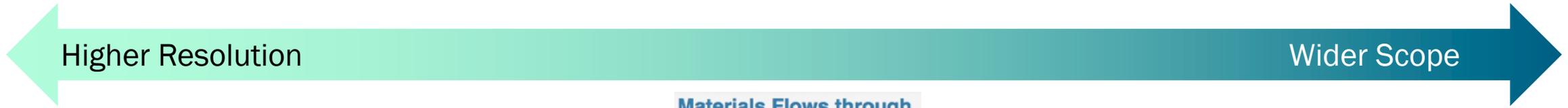
Approach: Team and research task structure



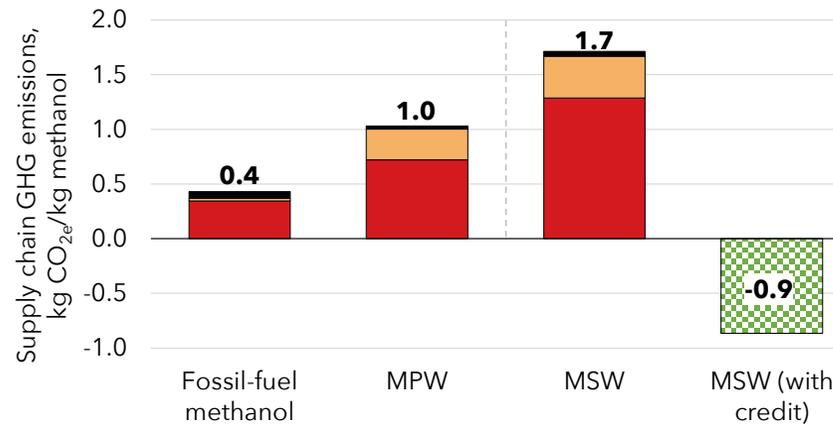
Since FY21, BOTTLE onboarded a **Chief Technology Officer (CTO)** and **Technical Advisory Board (TAB)**

Analysis-guided R&D is the foundation of BOTTLE's approach

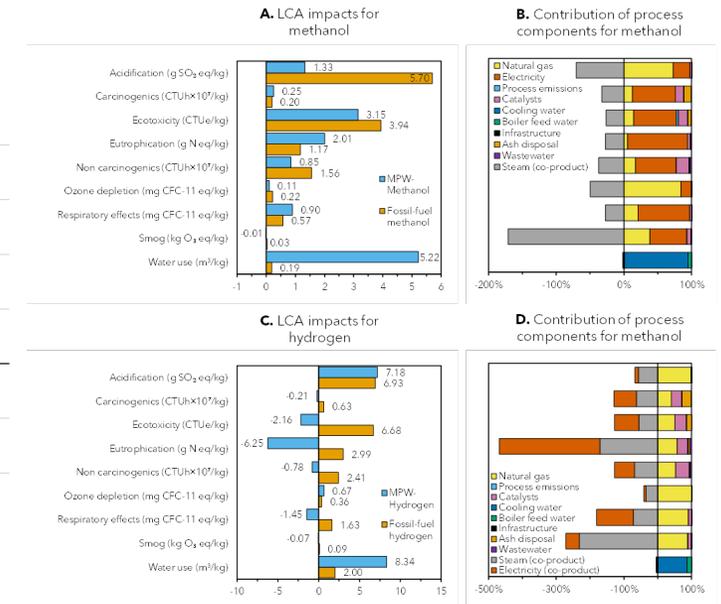
Example: Gasification of plastic waste to MeOH



Process modeling & TEA



Supply chain energy and GHGs



Comprehensive LCA

Metrics for BOTTLE projects – Aligning with DOE’s SPI

Energy:

- $\geq 50\%$ energy savings relative to virgin material production
- Closed-loop recycling estimated to save 40-90% energy

Carbon:

- $\geq 75\%$ carbon utilization from waste plastics
- Estimated based on recycling of commodity thermoplastics

Economics:

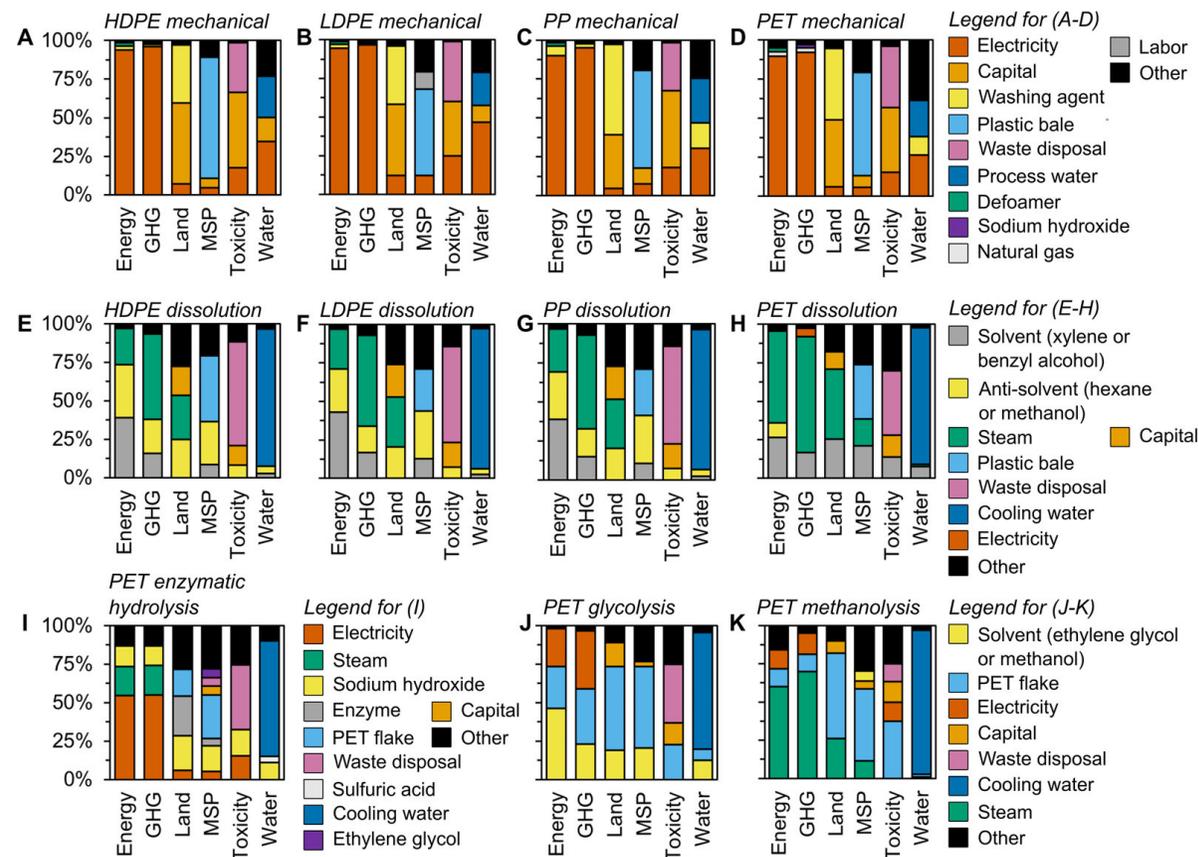
- $\geq 2x$ economic incentive over reclaimed materials

GHG emissions reductions:

- $\geq 50\%$ GHG emissions reduction compared to virgin manufacturing

Directly aligns to DOE’s Strategy for Plastics Innovation (SPI) objectives and metrics

TEA/LCA baseline of current recycling technologies



Key challenges in BOTTLE's Approach



Challenge 1 – Conducting TEA/LCA across entire BOTTLE portfolio

- Limited data available for early-stage research projects
- Develop best-case scenario initial models



Challenge 2 – Heterogeneity in plastic waste streams

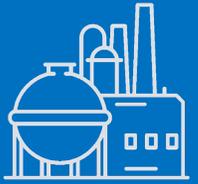
- Consistency challenges in variable feedstocks
- Limited by what is currently collected and sorted or can be sourced
- Key interactions with industry partners



Challenge 3 – Demonstrating scalability to industrial partners at early development stages

- Industrial partners often want a direct line of sight to scale
- Work towards bench-scale integration with real feedstocks as soon as feasible

BOTTLE project risks and mitigation plans



Risk: Limited current capabilities for rapid scaling of promising BOTTLE technologies

Mitigation: Expand interactions within BOTTLE institutions and identify key groups/teams with experience and equipment in scaling and piloting new technologies



Risk: Unable to produce RBD polymers at commodity prices and achieve >50% energy savings relative to today's materials

Mitigation: Conduct analyses of the full polymer life cycle in a linear economy case compared to a circular case to quantify the life cycle energy and economic potential; address monomer manufacturing directly



Risk: The BOTTLE carbon metric might not be achievable in all technology cases

Mitigation: Will evaluate maintaining or off-boarding work when energy and economics metrics are exceeded but carbon metrics cannot be met; will assess relative importance of metrics with comprehensive analysis tools

Collaboration and communication

- Centralized industry engagement and communications efforts

Within BOTTLE:

- Fortnightly BOTTLE R&D meetings include “hot data” and forum for early career researchers to share unpublished work
- Monthly meetings with DOE Technology Managers
- Use Dropbox for data sharing, Slack for communication
- In-person All-Hands meeting with TAB in June 2022
- Shared TAB report with team and updated BOTTLE strategies based on feedback
- Deliver a BOTTLE “portfolio analysis” to BETO/AMMTO Technology Managers to share BOTTLE’s key capabilities

External communication:

- Slack channel with TAB to share papers and updates
- Work with BETO and AMMTO Communications to send out e-blasts on exciting research
- Created BOTTLE Twitter and Instagram accounts

The BOTTLE Consortium & TAB All Hands 2022



ENERGY.GOV

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Bioenergy Technologies Office

October 21, 2022

BOTTLE Project Outlines New Two-Step Process for Turning Mixed Plastic Waste into Valuable Bioproducts

BOTTLE Diversity, Equity, and Inclusion (DEI)



Framework complete, developing finalized, detailed plan

BOTTLE's DEI Statement: A diverse and inclusive consortium which fosters the growth of researchers across their career, engages broadly to educate the public on our work, and ultimately contributes to a decarbonized materials economy on both the local community level and the world broadly

Selected DEI Accomplishments to date

Development

- Hiring GEM/SULI interns at multiple BOTTLE labs
- Providing networking and development opportunities for early career researchers
- DEI training for all members planned at All hands
- EJ/SJ speaker series

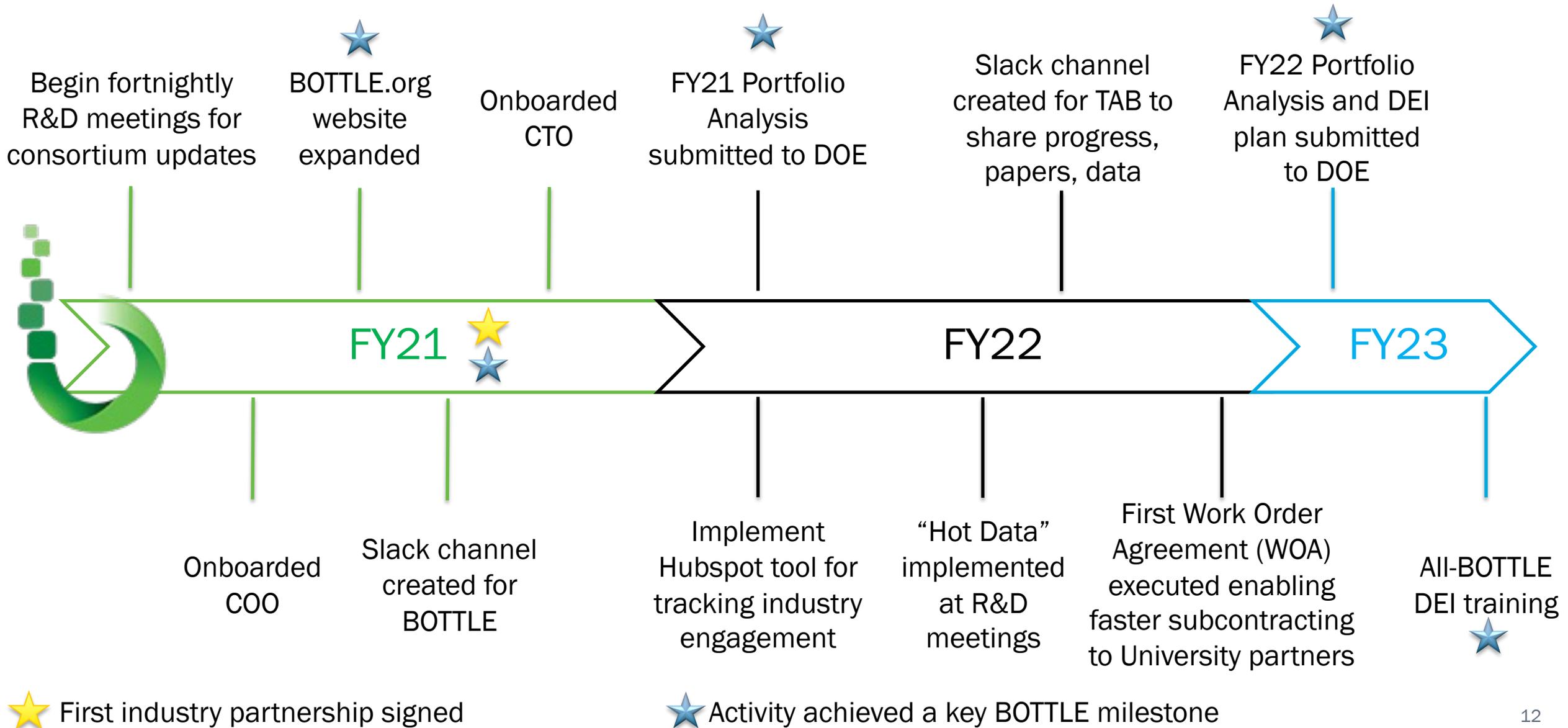
Outreach

- Presentations at MSIs (U Nevada, CCNY)
- Collaboration with an MSI (Hawaiian Pacific)
- Presentations at local high schools
- Participation in URG events (NOBCChE)

Community Change

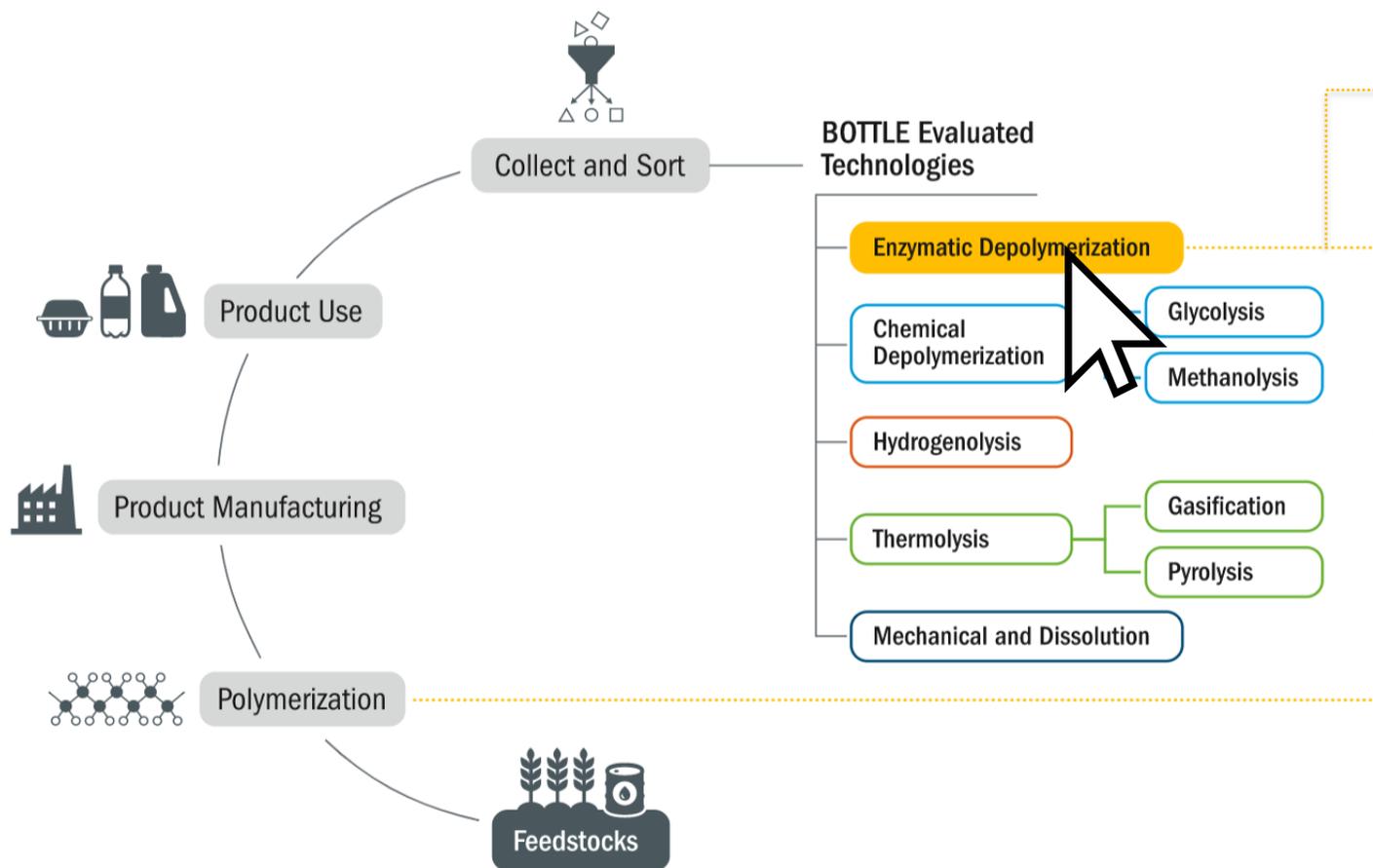
- Active project to develop a framework to examine Environmental & Social Justice of early TRL technologies into analysis work – will be applied to all BOTTLE projects

Progress: BOTTLE operations



Highlighting analysis-guided research on BOTTLE website

Excerpt from BOTTLE website Analysis page:



Joule
CellPress
Volume 5, Issue 9, 15 September 2021, Pages 2479-2503

Article
Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate)

Avantika Singh^{1,2}, Nicholas A. Rorrer^{1,3}, Scott R. Nicholson^{1,4}, Erika Erickson^{1,3}, Jason S. DesVeaux^{1,2}, Andre F.T. Avelino⁴, Patrick Lamers⁴, Arpit Bhatt⁴, Yimin Zhang⁴, Greg Avery⁴, Ling Tao², Andrew R. Pickford^{1,5}, Alberta C. Carpenter^{1,4}, John E. McGeehan^{1,5}, Gregg T. Beckham^{1,3,6}

Issue 17, 2022
From the journal: **Green Chemistry**

Life cycle assessment of enzymatic poly(ethylene terephthalate) recycling†

Check for updates

Taylor Uekert^a, Jason S. DesVeaux^{b,c}, Avantika Singh^{b,c}, Scott R. Nicholson^{a,b}, Patrick Lamers^b, Tapajyoti Ghosh^a, John E. McGeehan^d, Alberta C. Carpenter^{a,b} and Gregg T. Beckham^{b,c}

- New interactive figure on BOTTLE website will highlight key Analysis publications
- Viewers can hover over technologies to view pathways in the circular supply chain as well as relevant publications

Portfolio analysis within BOTTLE

Using active project management and analysis as a guide, the SLT compiles an annual portfolio review for DOE to evaluate technologies with potential for success and redeploy resources to the greatest opportunities

Summary of decisions to date



Accelerate

- hydrogenolysis for polyolefin deconstruction
- oxidation of mixed plastic waste
- RBD polyethylene
- designer PHAs



Discontinue (or completed)

- photocatalytic deconstruction
- electrocatalytic deconstruction
- biosensor development
- RBD nylons
- hyperbranched polyethylene



Major continuation decisions in FY23

- oxidative deconstruction
- enzymatic deconstruction of PET
- directed evolution for enzymatic deconstruction of PET and nylon
- catalyzed glycolysis of polyesters
- engineering *Geobacillus* for the conversion of PET

BOTTLE's Technical Advisory Board

Arizona State University



Tim Long – Chair

University of Delaware



Thomas Epps

Ocean Plastic Recovery



Scott Farling

BASF Enzymes



Adrienne Huston-Davenport

3M



Guy Joly

Sea Education Association



Kara Lavender-Law

Univ. of CA – Santa Barbara



Susannah Scott

Iowa State University



Brent Shanks

Univ. of MA – Lowell



Margaret Sobkowicz-Kline

The Ocean Foundation



Mark Spalding

Miliken



Scott Trenor

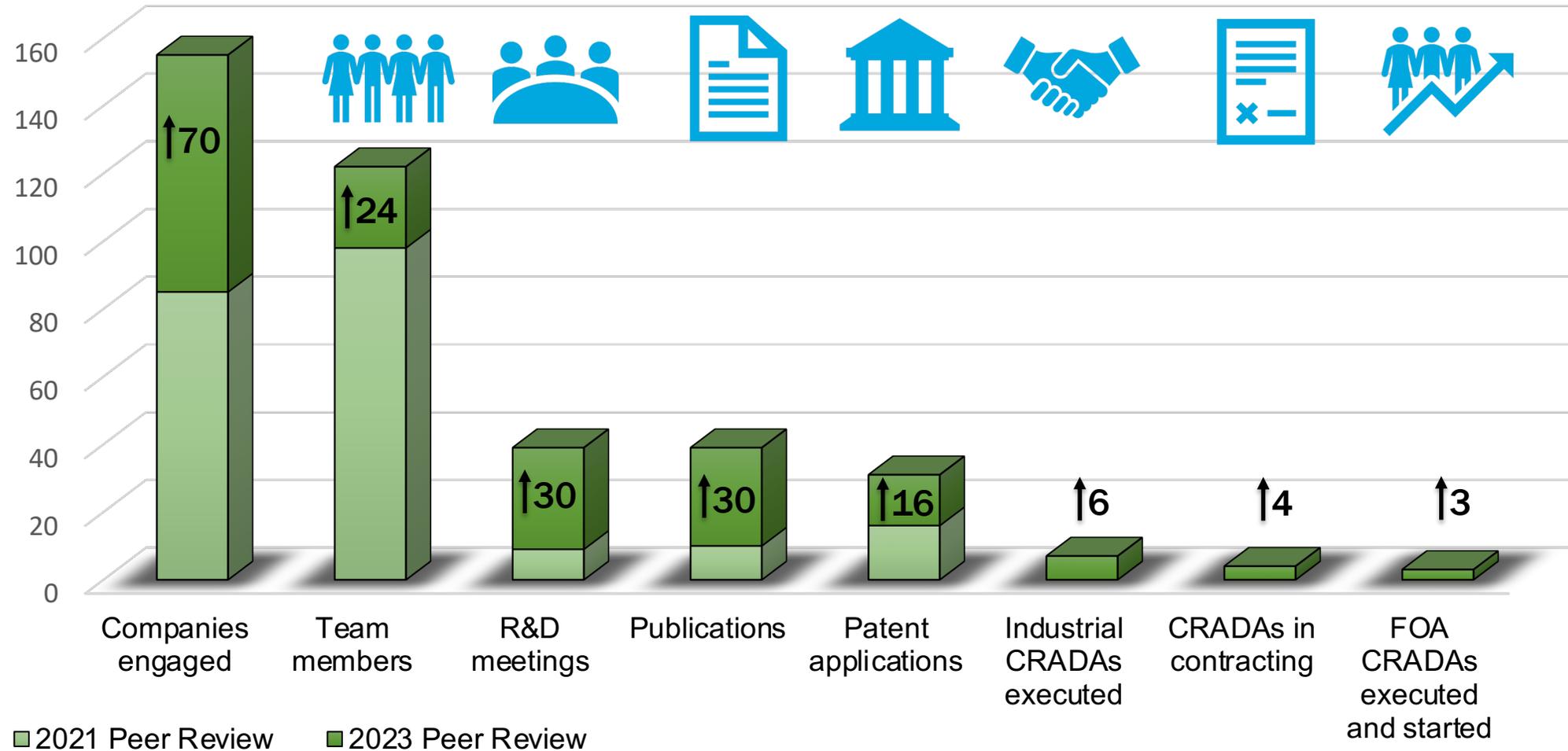
Role of the TAB:

- Feedback on R&D, operations, management
- Convene annually with the All-Hands meeting
- Provide written evaluations to DOE, BOTTLE LT

Excerpt from 2022 Report:

TAB recognized the excellent organization and management, comprehensive and evolving science leadership team, and attention to interdisciplinary teaming to ensure success

Impact: BOTTLE growth



Impact

- Development framework for circularity analysis – attracting engagement from industry, NGOs, and academic partners
- Substrate characterization methods proposed for reproducibility (Ellis *et al.*, *Nature Catal.* 2021)
- Training next-generation leaders in polymer sustainability and conducting active outreach
- Combining chemistry & biology to valorize mixed plastic waste and to produce monomers for recyclable-by-design polymers
- High-impact publications are attracting industrial partners who have identified BOTTLE technologies as promising solutions for plastic deconstruction, upcycling, and redesign

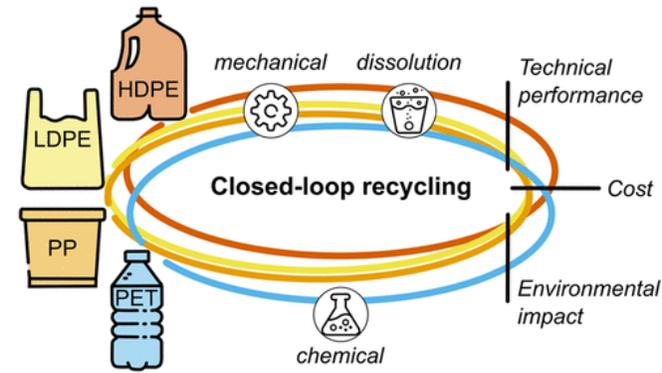


Image from Uekert *et al.*, *ACS Sustainable Chem. Eng.* 2023

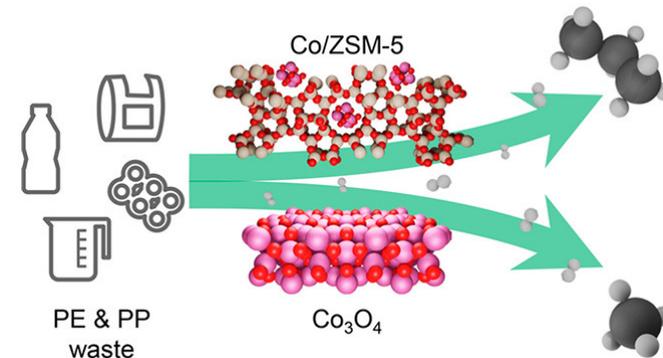


Image from Zichittella *et al.*, *JACS AU* 2023

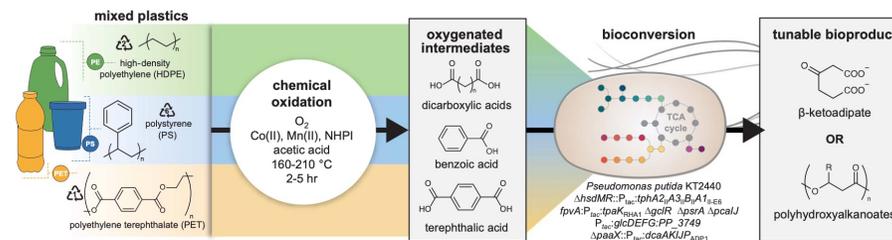


Image from Sullivan, Werner, Ramirez, Ellis, *et al.*, *Science* 2022

Resulted in:

- 4+ industrial contacts
- 32 news outlets



Resulted in:

- 2+ industrial contacts
- 31 news outlets



Resulted in:

- 10+ industrial contacts
- 80 news outlets



Summary

Overall:

- BOTTLE conducts interdisciplinary, industry-relevant, and process-enabling research to deconstruct and upcycle today's plastics and redesign tomorrow's plastics

Approach:

- BOTTLE is analysis guided and uses a Portfolio Analysis process to on/offboard projects with input from DOE

Progress and Outcomes:

- Onboarded a CTO and Technical Advisory Board
- Drafted a BOTTLE DEI framework

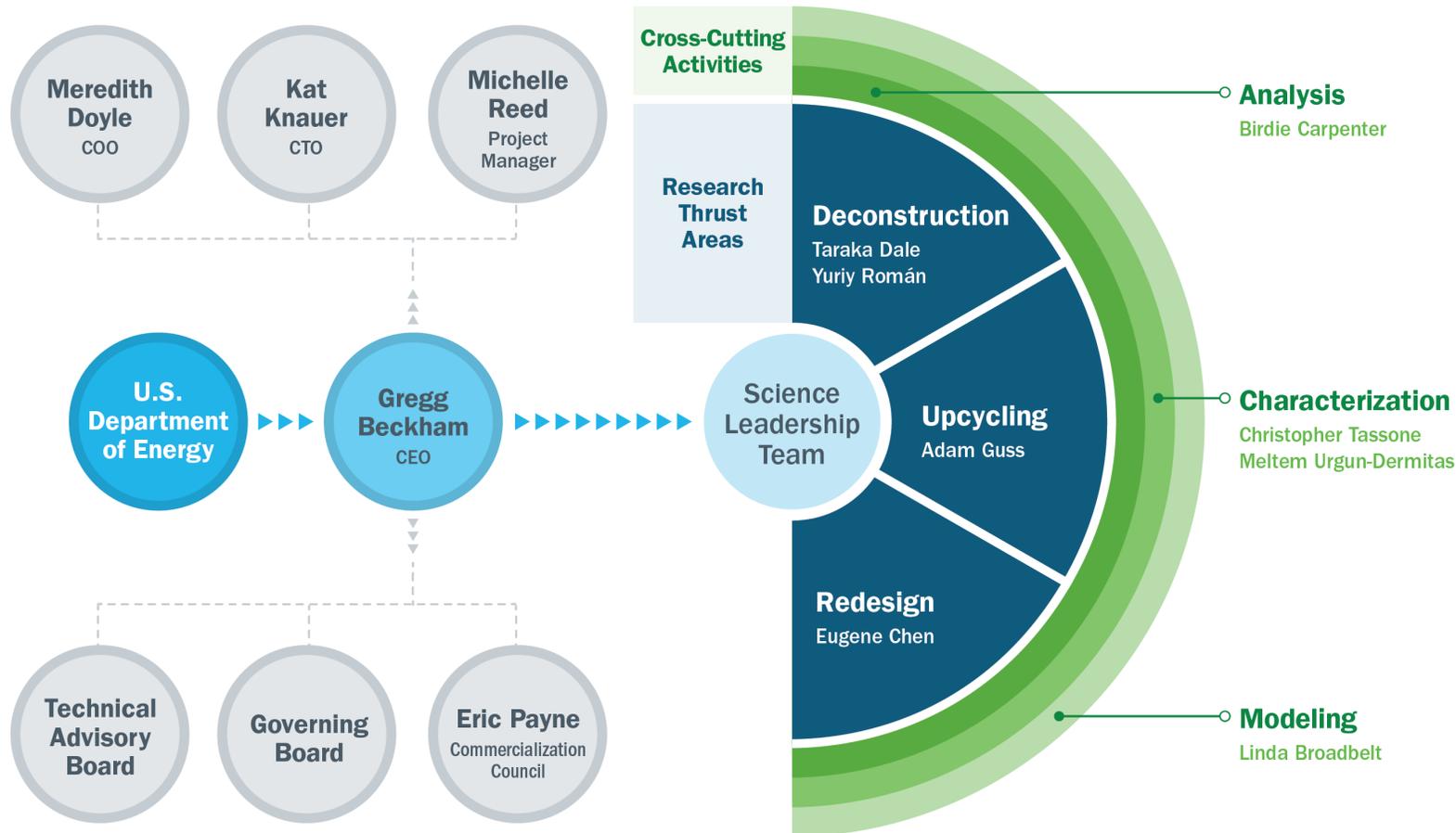
Impact:

- 6 funds-in CRADA industrial partnerships executed, 4 in contracting
- 40 publications, 32 patent applications to date



Additional Slides

Leadership Team Structure



BOTTLE Leadership Team (LT):

- CEO, COO, & PM
- Oversee the Management task
- *Role focused on leadership of BOTTLE*

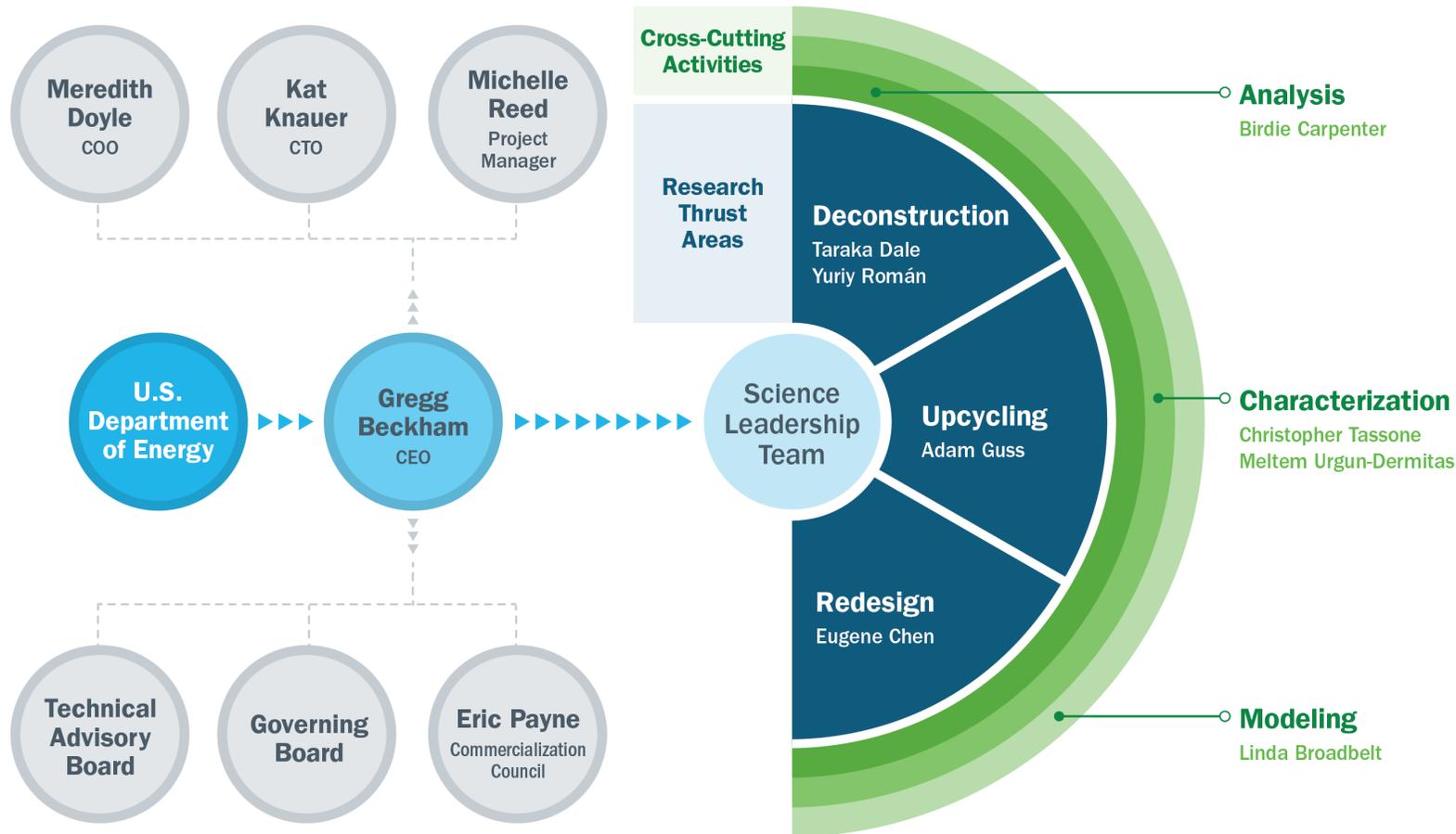
Governing Board (GB):

- BOTTLE LT, lab and several univ. leads, DOE
- Yearly strategic planning meeting
- *Role focused on management, strategy*

Science Leadership Team (SLT):

- CEO, all institutional leads, DOE
- Yearly planning meeting, teleconferences quarterly
- *Role focused on research execution*
- Annual Portfolio Review responsibilities
- Implement and supervise research projects at each institution

Technical Advisory Board and Comm. Council



Technical Advisory Board (TAB):

- Feedback on R&D, operations, management
- Invited diverse group of thought leaders from academia, government, industry, non-profits
- TAB represents key points in the plastics value chain to ensure robust assessment of BOTTLE
- Convene annually with the All-hands meeting
- Provide written evaluations to DOE, BOTTLE LT
- Includes leads of complementary R&D efforts in this space

Commercialization Council:

- Representative from each partner institution
- Central “storefront” for accessing BOTTLE IP through partnership and licensing
- Promote rapid deployment of BOTTLE IP

Publications

In preparation

Amy A. Cuthbertson, Clarissa L. Lincoln, Joel Miscall, Lisa Stanley, David T. Moore, Brenna A. Black, Nicholas A. Rorrer, Gregg T. Beckham, Characterization of polymer properties and identification of additives in commercial research plastics, in preparation.

Shaik Afzal, Avantika Singh, Scott R. Nicholson, Taylor Uekert, Eric C.D. Tan, Abhijit Dutta, Robert M. Baldwin, Gregg T. Beckham, Techno-economic analysis of mixed plastic waste gasification for the production of methanol and hydrogen, in preparation for *Energy Env. Sci.*

Rosie Graham, Erika Erickson, Richard K. Brizendine, Davinia Salvachúa, Zhongping Tan, Gregg T. Beckham, John E. McGeehan, and Andrew R. Pickford, Enzymatic deconstruction of poly(ethylene terephthalate) is not improved by the use of carbohydrate-binding modules at industrially-relevant solids loadings, in preparation for *Chem Catalysis*.

Julie E. Rorrer, Amani M. Ebrahim, Ydna Questell-Santiago, Clara Troyano-Valls, Arun S. Asundi, Simon R. Bare, Christopher J. Tassone, Gregg T. Beckham, Yuriy Román-Leshkov, Selective hydrogenolysis of polyethylene and polypropylene waste to liquid hydrocarbons over bifunctional Ru/acid catalysts, in preparation.

Geetanjali Yadav, Avantika Singh, Abhijit Dutta, Scott R. Nicholson, Kylee Harris, Calvin Mukarakate, Joshua A. Schaidle, Cody J. Wrasman, Yuriy Román-Leshkov, Robert M. Baldwin, Gregg T. Beckham, Techno-economic analysis of pyrolysis of mixed plastics waste, in preparation for *Energy Env. Sci.*

Submitted

Houqian Li, Robert D. Allen, Xianglan Bai, Gregg T. Beckham, et al., Expanding plastics recycling technologies: chemical aspects, technology status and challenges, submitted to *ACS SusChemEng*.

Publications

In review

Richard K. Brizendine, Erika Erickson, Stefan J. Haugen, Kelsey J. Ramirez, Joel Miscall, Davinia Salvachúa, Andrew R. Pickford, Margaret J. Sobkowicz-Kline, John E. McGeehan, Gregg T. Beckham, Effect of particle size and substrate crystallinity on enzymatic depolymerization of poly(ethylene terephthalate), in review at ACS SusChemEng.

Kevin P. Sullivan, Allison Z. Werner, Kelsey J. Ramirez, et. al., Tandem chemical oxidation and biological funneling for upcycling of mixed plastic waste, in review at Science.

In revision

Anelia Milbrandt, Kamyria Coney, Alex Baggett, Gregg T. Beckham, Quantity, distribution, market value, and energy value of plastic waste in the United States, in revision at Resources, Conservation, and Recycling.

Allison Z. Werner, Rita Clare, Thomas D. Mand, et. al, Tandem chemical deconstruction and biological upcycling of poly(ethylene terephthalate) to b-ketoadipic acid by *Pseudomonas putida* KT2440, In revision at Metabolic Engineering.

In press

Scott R. Nicholson, Julie E. Rorrer, Avantika Singh, Mikhail O. Konev, Nicholas A. Rorrer, Alberta C. Carpenter, Alan J. Jacobsen, Yuriy Román-Leshkov, Gregg T. Beckham, The critical role of process analysis in chemical recycling and upcycling of waste plastics, in press at Ann. Rev. Chem. Biomolec. Eng.

Publications

2023

Taylor Uekert, Avantika Singh, Jason S. DesVeaux, Tapajyoti Ghosh, Arpit Bhatt, Geetanjali Yadav, Shaik Afzal, Julien Walzberg, Katrina M. Knauer, Scott R. Nicholson, Gregg T. Beckham, and Alberta C. Carpenter, “Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics,” *ACS Sustainable Chemistry & Engineering* (2023) 11, 3, 965–978.

2022

Taylor Uekert, Scott R. Nicholson, Avantika Singh, Jason S. DesVeaux, Tapajyoti Ghosh, John E. McGeehan, Alberta C. Carpenter, Gregg T. Beckham, “Life cycle assessment of enzymatic poly (ethylene terephthalate) recycling,” *Green Chemistry* (2022) 24, 6531-6543.

Guido Zichittella, Amani M. Ebrahim, Jie Zhu, Anna E. Brenner, Griffin Drake, Gregg T. Beckham, Simon R. Bare, Julie E. Rorrer, and Yuriy Román-Leshkov, Hydrogenolysis of polyethylene and polypropylene into propane over cobalt-based catalysts, *JACS Au.* (2022) 2, 10, 2259–2268.

Kevin P. Sullivan, Allison Z. Werner, Kelsey J. Ramirez, et. al., Mixed plastics waste valorization through tandem chemical oxidation and biological funneling, *Science* (2022) 378, 207-211.

Rosie Graham, Erika Erickson, Richard K. Brizendine, Davinia Salvachúa, William E. Michener, Yaohao Li, Zhongping Tan, Gregg T. Beckham, John E. McGeehan, Andrew R. Pickford, The role of binding modules in enzymatic poly(ethylene terephthalate) hydrolysis at high-solids loadings, *Chem. Catalysis.* (2022) 2644-2657.

Sang-Min Shin, Ramesh K. Jha, and Taraka Dale, Tackling catch-22 situation of optimizing a sensor and transporter system in a whole cell biosensor design for an anthropogenic small molecule, *ACS Synthetic Biology* (2022), 11, 3996-4008.

Publications

Julie E. Rorrer, Amani M. Ebrahim, Ydna Questell-Santiago, Jie Zhu, Clara Troyano-Valls, Arun S. Asundi, Anna E. Brenner, Simon R. Bare, Christopher J. Tassone, Gregg T. Beckham, and Yuriy Román-Leshkov, The role of bifunctional Ru/acid catalysts in selective hydrocracking of polyethylene and polypropylene waste to liquid hydrocarbons, *ACS Catal.* (2022) 12, 22, 13969–13979.

Andrea H. Westlie, Eugene Y.-X. Chen, Chris M. Holland, Shannon S. Stahl, Meredith Doyle, Scott R. Trenor, Katrina M. Knauer, Polyolefin innovations towards circularity and sustainable alternatives, *Macromolecular Rapid Communications* (2022) 43, 2200492.

Raka G. Dastidar, Min Soo Kim, Panzheng Zhou, Zaneta Luo, Changxia Shi, Kevin J. Barnett, Daniel J. McClelland, Eugene Y.-X. Chen, Reid C. Van Lehn, George W. Huber, Catalytic production of tetrahydropyran (THP): a biomass-derived, economically competitive solvent with demonstrated use in plastic dissolution, *Green Chem.* (2022) 24, 9101–9113.

Zhen Zhang, Changxia Shi, Miriam Scoti, Xiaoyan Tang, and Eugene Y.-X. Chen, Alternating Isotactic Polyhydroxyalkanoates via Site- and Stereoselective Polymerization of Unsymmetrical Diolides, *J. Am. Chem. Soc.* (2022), 144, 20016–20024.

Andrea H. Westlie, Ethan C. Quinn, Celine R. Parker, Eugene Y.-X. Chen, Synthetic biodegradable polyhydroxyalkanoates (PHAs): recent advances and future challenges, *Prog. Polym. Sci.* (2022), 134, 101608.

Erika Erickson, Japheth E. Gado, Luisana Avilán, et al., Sourcing thermotolerant poly(ethylene terephthalate) hydrolase scaffolds from natural diversity, *Nat Comm.* (2022) 13, 7850.

Robin M. Cywar, Nicholas A. Rorrer, Heather B. Mayes, Anjani K. Maurya, Christopher J. Tassone, Gregg T. Beckham, Eugene Y.-X. Chen, Redesigned hybrid nylons with optical clarity and chemical recyclability, *J. Am. Chem. Soc.* (2022) 144, 5366–5376.

Publications

Coralie Jehanno, Jill W. Alty, Martijin, Steven De Meester, Andrew P. Dove, Eugene Y.-X Chen, Frank A. Leibfarth, Haritz Sardon, Critical advances and future opportunities in upcycling commodity polymers, *Nature* (2022), 603, 803–814.

William M. Kincannon, Michael Zahn, Rita Clare, Jessica Lusty Beech, Ari Romberg, James Larson, Brian Bothner, Gregg T. Beckham, John E. McGeehan, and Jennifer L. DuBois, Biochemical and structural characterization of an aromatic ring-hydroxylating dioxygenase for terephthalic acid catabolism. *Proc. Natl. Acad. Sci.* (2022) 19(13):e2121426119.

Jessica Lusty-Beech, Rita Clare, William M. Kincannon, Erika Erickson, John E. McGeehan, Gregg T. Beckham, Jennifer L. DuBois, A flexible kinetic assay efficiently sorts prospective biocatalysts for PET plastic subunit hydrolysis. *RSC Adv.* (2022) 12, 8119-8130.

Changxia Shi, Ryan W. Clarke, Michael L. McGraw, Eugene Y.-X., Closing ‘one monomer–two polymers–one monomer’ loop via orthogonal (de)polymerization of a lactone/olefin hybrid, *J. Am. Chem. Soc.* (2022) 144, 2264–2275.

Erika Erickson, Thomas Shakespeare, Felecia Bratti, Bonnie L. Buss, Rosie Graham, McKenzie Hawkins, Gerhard König, William E. Michener, Joel Miscall, Kelsey J. Ramirez, Nicholas A. Rorrer, Michael Zahn, Andrew R. Pickford, John E. McGeehan, Gregg T. Beckham, “Comparative PETase performance as a function of reaction conditions, substrate properties, and product accumulation,” *ChemSusChem* (2022) 15, e202101932.

2021

Bing Yan, Changxia Shi, Gregg T. Beckham, Eugene Y. X. Chen, Yuriy Román-Leshkov, Electrochemical activation of C-C bonds via mediated hydrogen atom transfer reactions, *ChemSusChem* (2021) 15,6, e202102317.

Publications

Changxia Shi, Liam T. Reilly, Vi Sai Phani Kumar, Matthew W. Coile, Scott R. Nicholson, Linda J. Broadbelt, Gregg T. Beckham, Eugene Y.-X. Chen, Design principles for intrinsically circular polymers with tunable properties, *Chem* (2021), 7, 2896–2912.

Julie E. Rorrer, Clara Troyano-Valls, Gregg T. Beckham, and Yuriy Román-Leshkov, Hydrogenolysis of polypropylene and mixed polyolefin plastic waste over Ru/C to produce liquid alkanes, *ACS Sustainable Chemistry & Engineering* (2021) 9, 35, 11661-11666.

Elani Lacovidou, Richard Geyer, Julia Kalow, James Palardy, Jennifer Dunn, Timothy Hoellein, Eugene Y.-X. Chen, Toward a circular economy for plastics, *One Earth* (2021), 4, 591–594 (Featured as Voices article).

Lucas D. Ellis, Nicholas A. Rorrer, Kevin P. Sullivan, et al. Chemical and biological catalysis for plastics recycling and upcycling. *Nature Catal.* (2021) 4, 539–556.

Lucas D. Ellis, Sara V. Orski, Grace A. Kenlaw, Andrew G. Norman, Kathryn L. Beers, Yuriy Román-Leshkov, Gregg T. Beckham, Tandem heterogeneous catalysis for polyethylene depolymerization via an olefin intermediate process, *ACS Sustainable Chemistry & Engineering* (2021) 9, 623-628.

Scott Nicholson, Nicholas A. Rorrer, Alberta C. Carpenter, and Gregg T. Beckham, Manufacturing energy and greenhouse gas emissions associated with plastics consumption, *Joule* (2021) 5, 3, 673-686.

Changxia Shi, Zi-Chen Li, Lucia Caporaso, Luigi Cavallo, Laura Falivene, Eugene Y.-X., Hybrid monomer design for unifying conflicting polymerizability, recyclability, and performance properties, *Chem* (2021), 7, 670–685.

Patents and patent applications

- Synergistic dual cure for rapid manufacturing of thermoset material, 22-71: U.S. provisional patent application 63/414,238
- Base-mediated method for the recycling of epoxy resin-carbon fiber composites, 22-130: U.S. provisional patent application 63/418,874
- Renewable bio-advantaged plasticizer generated by reductive cross coupling of lignin-derived aromatics, 22-124: U.S. provisional patent application 63/379,217
- Process for sequential acetolysis-oxidation of plastic streams, 22-107: U.S. provisional patent application 63/383,293
- Methods and systems for dye removal from polymer textiles, 22-106: U.S. provisional patent application 63/384,137
- Biodegradable elastomeric thermosets from microbially-produced polyhydroxyalkanoates, 19-104: U.S. provisional patent application 63/386,011
- Light-driven C-C bond cleavage enabled by polyoxometalate photocatalysts, 21-95: U.S. provisional patent application forthcoming

Patents and patent applications

- Hydrogenolysis of Polyethylene and Polypropylene into Propane over Cobalt-Based Catalysts, 22-81: U.S. provisional patent application 63/340,322
- Catalysts for Depolymerizing Plastics, 20-22: 17/370,244
- Plastic Degrading Fusion Proteins and Methods of Using the Same, 20-86: PCT/US21/31610
- Polymer Degrading Enzymes, 21-88: PCT/US22/25624.
- Dissolution Purification and Recovery for Polymeric Recycling, 22-16: 63/307,676
- Method to Produce Branched-Chain Polyhydroxyalkanoates and Branched Chain 3-Hydroxyacids from Glucose, 21-63A: 63/321,207.
- Upcycling Mixed Waste Plastic Through Chemical Depolymerization and Biological Funneling, 20-123: PCT/US21/63725.
- Genetically engineered Pseudomonas strains capable of metabolizing ethylene glycol, 17-26: 11,021,721
- Engineered Pseudomonas for the Deconstruction of Polymers, 18-76: 17/055,626
- Microorganisms Engineered for Muconate Production, 20-48: 17/184,580

Patents and patent applications

- Polymers from bio-derived dicarboxylic acids (BKA to nylon), 17-48: 10,662,289
- Polymers and methods of making the same (PET formulated with adipic/muconic acids), 17-55A: 17/205,232
- Monomers, Polymers and Methods of Making the Same (Bio-plastic ABS), 18-69: 16/583,471
- Bio-derived biphenyl compounds (Polycarbonates), 18-81: 16/791,873
- Bioderived monomers as replacements in petroleum-based polymers and copolymers (novel bio-based plasticizers), 19-38: 16/790,093
- Conversion of dicarboxylic acids to monomers and plasticizers, 19-41A: 16/995,338
- Bio-derived Epoxide Triazine Networks and Methods of Making the Same, 20-26: 17/324,222
- Bio-derived Epoxy-Anhydride Thermoset Polymers for Wind Turbine Blades and Anti-Static Coatings, 20-59: 17/494,514
- Plastic waste derived polymers and resins and methods of making the same (PET upcycled to 3D printing materials). 20-37: 17/371,421
- Mixed Waste Plastics Compatibilizers for Asphalt (filed by ASU), 21-53: 63/148,423

Patents and patent applications

- Bioderived Benzoxazines, 20-130: 17/690,131
- Novel Routes to Bis-furan Diacids, Dialcohols and Diamines, US 9840485
- Improved Industrial Production of Isotactic Polylactides (PLA), US 10174161
- Chemically Recyclable Polymers to Combat Single-Use Plastics, PCT Patent Pending: WO 2021/113325
- Synthesis of Crystalline Polymers from Cyclic Diolides, US Utility Patent Pending: US 2019/0211144
- Novel Compounds and Methods for Upgrading Biomass to Produce Premium Biofuels, US Utility Patent: US 9469626 B2, US Utility Patent: US 9828354 B2
- High-Speed, Stereoselective Polymerization for Renewable Bio-derived Plastics, US Utility Patent: US 9309332

Presentations

Selective Hydrogenolysis of Polyolefin Waste to Liquid Hydrocarbons over Bifunctional Ru/Acid Catalysts, AIChE National Conference, November 15, 2022.

Developing Strategies for Polymer Redesign and Recycling Using Reaction Pathway Analysis, AIChE Annual Meeting, November 2022.

Development of non-model microbes as chassis organisms for bioconversion. Presented at the AIChE Annual Meeting, November 2022.

Redesigning Polymers to Leverage a Circular Economy, Chemical Engineering, Purdue University, November 2022.

Bio-based Polymers with Performance & Recyclability Advantages, Braskem, virtual seminar, November 2022.

Design Principles and Chemocatalytic Methods for Circular Polymers and Biodegradable Plastics, BASF Lecture in Organic Chemistry, November 2022.

Developments in Advanced Recycling, TA Instruments Webinar, October 2022.

Design of Polyolefin-like Polyesters with Closed-loop Lifecycles, ACS WRM Polymer Symposium, October 2022.

Adopting a sustainable plastics supply chain, RISE 2022, September 2022.

Presentations

Redesigning plastics to be recyclable-by-design, RISE 2022, September 2022.

Advances in lignin and plastics conversion, VITO, September 2022.

Decoding the mechanism of autoxidation deconstruction reaction of plastics by in-situ simultaneous SAXS and WAXS,” XVIII International Small-Angle Scattering Conference (SAS2022), September 2022.

Design of functionalized polyolefins and polyolefin-like polyesters with close-loop chemical recycling, ACS Advances in Polyolefins, September 2022.

Using synthetic biology to solve challenges in plastic waste and renewable chemical production, Biological Sciences Departmental Seminar, September 2022.

Advancing the catalytic upcycling of waste polyolefin plastics, Beckman Foundation Regional Symposium, August 2022.

Using redesigned iron catalysts to bring aromatic subunits to a common intermediate, SIMB 2022, August 2022

Techno-economic analysis and life cycle assessment for catalytic fast pyrolysis of mixed plastic waste, BioEnergy TRP Meeting, National Renewable Energy Laboratory, August 2022.

Bio-based, recyclable-by-design polymers, ACS National Meeting, August 2022

Presentations

Techno-Economic analysis and life cycle assessment of mixed waste plastics via pyrolysis and gasification, ACS Fall Conference, August 2022.

Monomer design for circular polymers that unify conflicting properties, ACS Symposium: Design Polymers for Upcycling, ACS National Meeting, August 2022.

Bio-based acrylic plastics with performance and recyclability advantages, ACS Symposium: Green Polymer Chemistry and Sustainability, ACS National Meeting, August 2022.

Plastics recycling, upcycling, and redesign in the BOTTLE Consortium, ACS National Meeting, August 2022.

Plastics Deconstruction & Upcycling in the BOTTLE Consortium, ACS National Meeting, August 2022.

Design principles and chemocatalytic methods for intrinsically circular polymers and biodegradable plastics, ACS Presidential Event: Series-Enabling Circular Economy via Polymer Molecular Recycling, ACS National Meeting, August 2022.

Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate), ACS Fall Conference, August 2022.

Kinetic Monte Carlo-based tool to unravel solvolysis chemistry of step-growth polymers, National Meeting of the American Chemical Society, August 2022.

Presentations

Tracking in situ structural changes in Ru, Mo and Co-based hydrogenolysis catalysts for polyolefin deconstruction under mild temperature using in situ/operando X-ray absorption spectroscopy, ACS Fall Meeting: Polymer Upcycling Symposium, August 2022.

High throughput test tools for industrially relevant microbial chassis, SIMB 2022, August 2022.

Circular polymers and biodegradable plastics, Circular Polymers and Biodegradable Plastics International Research Training Group, University of Muenster, July 2022.

Engineering P450s to alleviate a bottleneck to lignin demethylation, Intl. Conference on Porphyrins and Phthalocyanines, July 2022.

Difficult to recycle plastics, Sustainable Packaging Coalition Engage Meeting, July 2022.

Selective chemical recycling of mixed plastics waste, Polymer Physics Gordon Research Conference, July 2022.

Plastics recycling and upcycling in the BOTTLE Consortium, NASEM Committee on Repurposing Plastic Waste, July 2022.

Developing strategies for polymer redesign and recycling using reaction pathway analysis, Gordon Research Conference on Polymer Physics, July 2022.

Multi-Material Flexible Packaging Coalition SPC, February 2022.

Presentations

Development of chemical recycling approaches for plastic waste (via webinar), BASF, March 18th, 2022

Development of chemical recycling approaches for plastic waste, Enzylic Consortium (via webinar), January 2022

Development of chemical recycling approaches for plastic waste, UIUC, December 2021

Design Principles and Synthetic Methodologies for Circular Polymers with Intrinsic Recyclability and Tunable Properties, Pacifichem Conference, December 2021

New building blocks for performance-advantaged renewable and recyclable polymers, Pacifichem (via webinar), December 2021

Discovery and characterization of PET degrading enzymes, University of Rochester microplastics workgroup seminar series, December 2021.

Design Principles and Synthetic Methodologies for Intrinsically Circular Polymers and Biodegradable Plastics, Columbia University, November 2021

Selective Hydrogenolysis of Polyethylene and Polypropylene to Liquid Alkanes over Tunable Ruthenium-Based Heterogeneous Catalysts, 2021 AIChE National Conference, Boston, MA, November 2021.

Plastics recycling and upcycling, ACS Converge (via webinar), October 2021

Presentations

Genetic tools and microbial engineering for biological production of sustainable fuels and chemicals, Presented to Weekly Seminar for DOE CCI/SULI Students. October 2021

Heterogeneous Catalytic Deconstruction and Upcycling of Waste Polyolefins, Biodesign Institute at Arizona State University, SM3 Seminar Series, October 2021.

Domestication of diverse non-model microbes for plastics upcycling and sustainable fuel and chemical production, Biological Sciences Departmental Seminar, Michigan Technical University. October 2021.

Catalysis for valorization of lignin and plastics, Great Plains Catalysis Society (via webinar), June 2021

The critical role of economic and environmental analysis to guide research in lignin valorization and plastics upcycling, Keynote Invited Lecture, ACS Green Chemistry and Engineering (via webinar), June 2021

Towards Intrinsically Circular Thermoplastics and Reprocessable Thermosets, Dow Chemical Company, virtual seminar, May 2021

Recent progress in performance-advantaged bioproducts and plastics upcycling, Arizona State University (via webinar), April 2021

Recent adventures in biomass conversion and plastics upcycling, Rutgers University (via webinar), April 2021

Presentations

Recent adventures in biological plastics upcycling, MIX-UP Consortium (via webinar), April 2021

Framing challenges and opportunities for chemical recycling of waste plastics, ACS Presidential Symposium on Chemistry and the Future of Plastics (via webinar), April 2021

Recent updates in plastics upcycling from the BOTTLE Consortium, ExxonMobil Research and Engineering, April 2021

Design Principles and Synthetic Methodologies for Circular Polymers and Biodegradable Plastics, KAUST, Physical Science and Engineering Division, virtual seminar, April 2021

Heme and non heme iron enzymes and renewable carbon, University of San Antonio Texas, April 2021

A flexible kinetic assay efficiently sorts potential biocatalysts for BHET hydrolysis, Symposium on Biomaterials, Fuels, and Chemicals, April 2021

BETO 2021 Peer Review, virtual, March 2021

Design Principles for Circular Plastics with Tunable Properties, CellPress LabLinks: The Circular Plastics Economy: Linking Across Scales, virtual event with 440 registered attendees. March 2021.

Process analysis for enzymatic PET recycling, Global Research and Innovation on Plastics annual meeting (via webinar), March 2021

Presentations

Polyolefin upcycling in the BOTTLE Consortium, Annual SPE meeting (via webinar), February 2021

Biological processes for lignin and plastics conversion, University of California Riverside (via webinar), January 2021